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## Inductive Telemetry on a Deep Ocean Surface Mooring

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### ABSTRACT

A long term engineering test of ocean data telemetry using inductive coupling is being performed offshore Bermuda as part of the ONR-sponsored Atlantic Long Term Oceanographic Mooring (AL TOMOOR) program. Inductive modems are general purpose telemetry devices which can be used with standard, plastic-jacketed steel mooring lines to transmit data between instruments in the water column and a receiver in the surface buoy.

The advantage of inductive coupling over electrically connected instrumentation is that expensive and unreliable electro-mechanical cables and terminations are not needed to accomplish real time data telemetry. The modems send and receive data via toroids clamped around the wire which act as single turn transformers. Data telemetered up the wire are sent at a rate of 1200 b/s; commands are sent down the wire at 300 b/s.

### INTRODUCTION

Woods Hole Oceanographic Institution has been working for a number of years to develop technologies to facilitate real time data collection. The motivations for this work are discussed in detail in [1]. Fundamental telemetry developments at WHOI have concentrated on the underwater telemetry problem while attempting to make intelligent use of available RF technology to solve the atmospheric telemetry problem. In addition

to inductive telemetry, programs in acoustic telemetry [2], [3], [4] and hardwired telemetry systems [5], [6] have been conducted or are presently underway. Examples of all three technologies have been successfully demonstrated in at-sea tests.

Inductive telemetry for moored arrays is not a new idea. Neil Brown in 1966 [7] developed an analog version for a surface mooring with distributed sensors. The Cyclesonde profiling instrument has also used a simple form of inductive telemetry to allow data telemetry from an instrument sliding along a mooring wire. In addition, a commercial vendor has recently advertised a simple inductive modem for shallow water applications. The attraction of the technique is that it uses the plastic-jacketed wire typical of oceanographic moorings for signal conduction. The seawater is used as the return path. No breaks in the wire are required because the signals are transferred from a split ferrite core placed around the wire with no direct electrical connection. This allows sensors or instruments to be located anywhere on the mooring and eliminates the need for expensive and sometimes unreliable electromechanical cables and their terminations. Tests performed at WHOI to look at the effects of breaks in the plastic jacket due to fishbite or other causes determined that relatively small breaks were easily tolerated [8]. In fact up to 30 cm of wire could be exposed before signal drop-out occurred.

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The primary disadvantage of the inductive technique is that power is not efficiently transferred in this way so batteries must be located at the modem. In addition, signal levels at the receiver are low and this makes them susceptible to contamination from noise.

Acoustic telemetry, which has the same advantages and disadvantages as inductive telemetry relative to electrically connected systems requires more complex and therefore more expensive hardware than inductive telemetry. Power requirements for acoustic telemetry are also higher as are bit error rates since the ocean acoustic channel is so much more complex than the electrical channel. In fact, steel mooring lines have similar electrical characteristics as a function of frequency, to twisted pair telephone wire [9]. Thus, off-the-shelf modem technology could be adapted directly to the underwater application.

Inductive telemetry is being used in another WHOI project, an expendable mooring. In this application a lower power version of the modem has been developed using somewhat higher frequencies [10] and achieving 1200 b/s telemetry in both directions. It is also planned for use with the new moored profiling instrument [11] under development at WHOI.

## INDUCTIVE MODEMS

The inductive modems used on the ALTOMOOR mooring were designed for two-way communication. For the ALTOMOOR application only the transmit capability is being utilized in the remotes and the buoy modem acts only as a receiver. Specifications for the modems are shown in Table 1. Their important features include the ability to send data at 1200 b/s (and receive at 300 b/s) at a power drain of 270 mW over a distance of 10,000 meters. Standby power drain is 5 mW

PARAMETER	SPECIFICATION
Frequency	1200/2200 Hz
Baud Rate	1200 uplink 300 downlink
Power Req.	270 mW active 5 mW wait
Size	30 cm long x 5 cm with lithium battery pack
Estimated Range	10,000 meters
Power/Bit (transmit)	$3 \times 10^{-4}$ J/b

Table 1. Inductive modem specifications

during the wait state when data from sensors can be received and stored.

For the ALTOMOOR program the modems were configured to be awake 100% of the time and to transfer data a few seconds after reception. This was done to eliminate the need for more complex interactions between the current meters and the modems. For the one year ALTOMOOR program, three lithium D cells were used to power the modems. Most of this energy is consumed during standby. Only a tiny fraction is used in transmission because the transmission duty cycle is only .01%.

The modem's signals are coupled to the mooring wire via split ferrite cores. The cores are 3 cm in diameter by 1.5 cm high with 150 turns of no. 30 wire. They are aligned in a specially designed clamp so that the two halves mate precisely when clamped around the mooring wire. This is important to obtain the necessary energy transfer efficiency. The mooring wire/seawater return acts as a single turn secondary winding. Grounding plates are

used at the top and bottom of the mooring to provide a connection to the seawater for the return path. Capacitors are placed in line at both grounding plates to avoid a DC electrical connection between the mooring wire and the seawater which could drive galvanic corrosion between the wire rope and the ground plate, which is made of a sintered copper.

Each modem consists of a two board set. An INTEL 80C51FA microcontroller on one board, interfaced to a SILICON SYSTEMS SSI 73K302L single-chip modem and associated analog components on the second. The modems are interfaced to either an S4 or VMCM current meter. Neither of these current meters works in a polled mode, but both will provide data automatically on a regular schedule. To accommodate the requirement for low power continuous operation, while waiting for data, and the addition of RS-485 communication, a daughter board was added. This board has two main components, a Microchip PIC-16C57 microcontroller and a LTC485 RS-485 or open collector SAIL interface. This board is always powered and the PIC acts as a buffer/formatter for the data from the current meters.

For the two S4 locations, 17 data characters are expected from the S4 once every hour. S4 communication is CMOS level RS-232 at 4800 baud. When the PIC receives the first S4 data character the remaining data must arrive within 2 seconds or the PIC assumes the reception is in error and received characters are discarded. Once 17 characters are received, space characters and parity bits are eliminated, a 2 character ID is placed before the data creating a 16 character packet. The PIC then switches the power ON to the 80C51/Modem board set, waits .4 seconds and then sends the packet to the 80C51 for inductive transmission. The PIC waits for an additional 3.5 seconds and then removes power from the modem board. The 3.5 second delay allows the modem

time to establish a stable carrier that is recognized by the receiver in the surface buoy and then transmit the data. The PIC then waits an additional 10 or 20 second delay and then sends the same data with a revised ID to the buoy controller via RS-485.

The VMCM current meter at 2000m depth requires special interface consideration. First the VMCM normal communication is 20 mA current loop using SAIL protocol at 300 baud. For power considerations this was modified to open collector SAIL and an open collector SAIL interface replaces the LTC485 on the PIC board. The VMCM is configured so that once addressed it provides a 30 character data packet and remains in an OPEN state. In the OPEN state it provides new data every 15 minutes. When first powered, the PIC buffer board addresses the VMCM to insure it is in the OPEN state and then starts a 15 minute wait period. If VMCM data are received within this period, the wait cycle is restarted. If data are NOT received after 15 minutes, the PIC readdresses the VMCM in an attempt to acquire data and the wait cycle restarts. After either four data receptions or four, 15 minute time-outs, the PIC powers the modem and sends two 16 character packets of the last data received. The first packet has an ID and the North, East and Temperature data plus 2 character of VMCM Time. The second packet is sent 10 seconds after the first and has a different ID with the North and East data replaced by Rotor 2 and Rotor 1 data.

The inductive modem in the surface buoy consists of the 80C51FA microcontroller and SILICON SYSTEMS SSI 73K302L single-chip modem and associated components including the RS-485 interface on one board. It operates by initializing the 73K302L modem and then waiting for the inductive carrier to be detected. With carrier present, each UPPER case HEX-ASCII

character received is passed on to the buoy controller via RS-485. Invalid received characters are ignored.

## ALTOMOOR EXPERIMENT

The ALTOMOOR mooring was deployed on March 20, 1993 from the R/V Cape Hatteras in 4200 meters of water. The deployment site ( $32^{\circ} 09.60' \text{N}$ ,  $60^{\circ} 19.32' \text{W}$ ) is 37 km from the southeast shore of Bermuda. This location is easily reached and monitored by the Bermuda Biological Station for Research (BBSR) vessel and at the same time provides the needed water depth for the experiments carried out on ALTOMOOR.

The configuration of the array, as shown in Figure 1, allowed several experiments to be conducted. These included:

- 1) Inductive telemetry
- 2) Wire telemetry via electromechanical (EM) cables
- 3) Monitoring of buoy and mooring motions at wave frequencies
- 4) Synthetic line fishbite resistance

The mooring is designed as a taut array with a scope of 1.0 prior to deployment and a scope of 1.05 after deployment (assuming a zero current profile). The stretch (launch transient elongation) of the synthetic and wire ropes accounts for the scope change. The design current profile used for the mooring design is as follows:

- 70 cm/sec at the surface
- 43 cm/sec at 500 meter depth
- 25 cm/sec at 2000 meter depth
- 10 cm/sec at 4000 meter depth

with linear interpolation between these depths.

The surface buoy is a 2.7m hemisphere made of surlyn foam and previously deployed for 18 months during the ESOM project [2].

An advanced engineering package is located inside the buoy instrument well and records buoy dynamic response to waves, wind and moored array forces (buoy motion package). The buoy motion package includes three angular rate sensors, one triaxial accelerometer, and one triaxial magnetometer. Also located in the instrument well are:

- system controller
- two Argos transmitters
- battery packs
- meteorological station

An underwater load cell is located at the bottom of the buoy and directly connected to the mooring line. Mooring tension data are sent to the buoy motion package.

The first section of the moored array (upper 2000m) consists of jacketed EM cable and jacketed wire rope. This section is located in the fishbite zone [12] and is therefore made up of components proven to be fishbite resistant. The two S4 current meters have both hardwire (RS485) and inductive telemetry to the surface buoy. The VMCM has only inductive telemetry. The mooring response instrument located at the end of the wire rope section is a self-recording package which monitors mooring dynamic behavior. Key components of this instrument include three accelerometers, a fluxgate compass, and a tension cell.

Three samples of reinforced Kevlar were provided by Du Pont Fibers and Composites Development Center for an evaluation of their resistance to long term environmental exposure. These samples are:

- 1) VETS 211 3/8" Kevlar rope with Kevlar/dacron braided jacket (control)
- 2) VETS 211 3/8" Kevlar rope with

Kevlar/dacron and 6 mils stainless steel wire strands jacket

- 3) VETS 211 3/8" Kevlar rope with Kevlar/dacron and 3 mils stainless steel wire strands jacket

Two sets of samples, each 20m long, were placed between 57 and 177m and three sets with each sample length of 30m were placed at 400m, 500m, 850m, and 1000m.

The lower part of the mooring consists of nylon rope and a short length of polypropylene rope used to avoid tangling of the heavier nylon with the glass balls (backup flotation for recovery) during deployment. A second mooring response instrument is located at the end of the 2025m shot of nylon and a self recording engineering instrument (tilt, tension, pressure, temperature) is just below it.

Three mesh packages containing biodegradable plastic samples were placed at 3700m, married to the nylon rope. These samples are part of a "Studies on Marine Microbial Degradation of Bioengineered Polymeric Packaging Material" project conducted by the WHOI Biology Department and supported by the US Army Natick RD&E Center.

The ALTOMOOR program is a one-year deployment with a maintenance trip scheduled seven months after installation. Operation of the array instrumentation is autonomous with most instruments recording their data internally. The current meters and meteorological station also transmit data on a regular schedule. The controller accepts and formats this time multiplexed data and once per hour transfers the collected data along with engineering data and a checksum to the Argos PTT. The PTT is configured with two IDs, each with eight, 256-bit buffers.

The controller is based on Motorola's

68HC11E2 microprocessor. The main card includes a real time clock, a dual one-shot, an RS485 receiver, 32 Kbytes of EPROM, 16 Kbytes of RAM, an RS232 interface, an open collector SAIL interface and a local 5 volt regulator.

The 68HC11 is programmed to spend most of its time in the WAIT mode waking only to service the various interrupts. The main program is simply a loop which reacts to flags that are set or cleared by the interrupts. The controller is also equipped with a "deadman" reset circuit which will reset the CPU within 0.5 seconds should the program fail to run. The real time clock has a separate reset pin so time is not lost if the deadman circuit triggers a reset.

The controller accepts data from the inductive modem receiver as 16 byte packets which are time multiplexed with data from the RS485 loop. All data are transferred to the buffers in the order received. Character strings in excess of 16 characters are truncated and character strings containing less than 16 characters are ignored. A packet is also ignored if all 16 characters are not received within 2 seconds. All non-HEX ASCII characters within these limitations are transferred as "C's" to the Argos buffers to both identify bad data and to eliminate problems with the Argos PTT which cannot deal with non-ASCII characters.

The S4 current meters are programmed to measure current for one minute every sixty minutes. The VMCM records current and temperature every fifteen minutes. S4 data are telemetered hourly via hardwire connection (RS485) and then via inductive telemetry. VMCM data are also telemetered hourly via the inductive link. The meteorological station collects wind and air temperature data once per hour (10-minute average). Sampling strategies for the non-

telemetry instrumentation will be described elsewhere.

## RESULTS

ALTOMOOR has been deployed about four months at the time this article is being written. Two problems have been encountered. First, the upper S4 stopped sending data about two weeks after deployment. Both the RS485 (hardwired) link and the inductive link failed at the same time. Whether this was due to a failure in the S4 or the inductive modem is unclear since either failure could cause this condition. We know, however, that the wiring, both the copper conductors and the connections to the steel armor used for the inductive link must be intact because the lower instruments use the same signal wires.

The second problem is more subtle and is illustrated in Figs. 3 and 4 which shows data collected during May for the lower S4. Fig. 3 shows hourly data telemetered via the hardwired RS485 link. There are virtually no errors in these data except those introduced by the satellite link which have been removed by use of the checksum appended to each Argos transmission. The inductively telemetered data, however, has a number of missing values caused by the system trapping non-ASCII characters prior to the satellite link. These non-ASCII characters appear occasionally in the 16-byte inductive message from each modem. Their frequency is not range dependent and for this reason, we do not believe that noise is the culprit. Our best guess at this point is that a phantom bit is occasionally being generated by the modem receiver when it enables the RS485 link, which happens each time a byte is received. This extra bit is then interpreted as the start of a character which is more often than not non-ASCII. We plan to repair this problem during the maintenance cruise by leaving the receiver powered during the complete data transfer.

This will have a negligible impact on power consumption. As can be seen in the figures, overall data loss due to this problem is qualitatively minor, but since we are collecting data only once per hour, it could have a negative impact on some analyses.

## CONCLUSIONS

The inductive telemetry technique has worked well on this first major test. Problems that have been encountered should be correctable and will be addressed during the maintenance cruise. The present modem design needs further optimization to reduce power consumption, particularly during the wait stage. We are pursuing a lower power design on another project which should reduce overall power consumption substantially.

Inductive telemetry is a promising technology for oceanographic arrays whether moored, drifting, or towed. A particularly interesting application is the moored profiler. This system, which is under development at WHOI, uses a small motor with traction drive to climb along a mooring line. The prototype unit draws only about one watt while moving at 30 cm/sec. It can be equipped with an inductive modem to provide a real time data link to the outside world. The inductive technique is also ideal for towed arrays where sensors can be positioned anywhere along an insulated steel cable and moved or replaced with ease. Eventually, we anticipate that inductive modems will be built into many oceanographic instruments, allowing them to be deployed along the mooring line rather than in line, thus simplifying the logistics of mooring deployment. As instruments are miniaturized, this should become more and more feasible.

## ACKNOWLEDGMENTS

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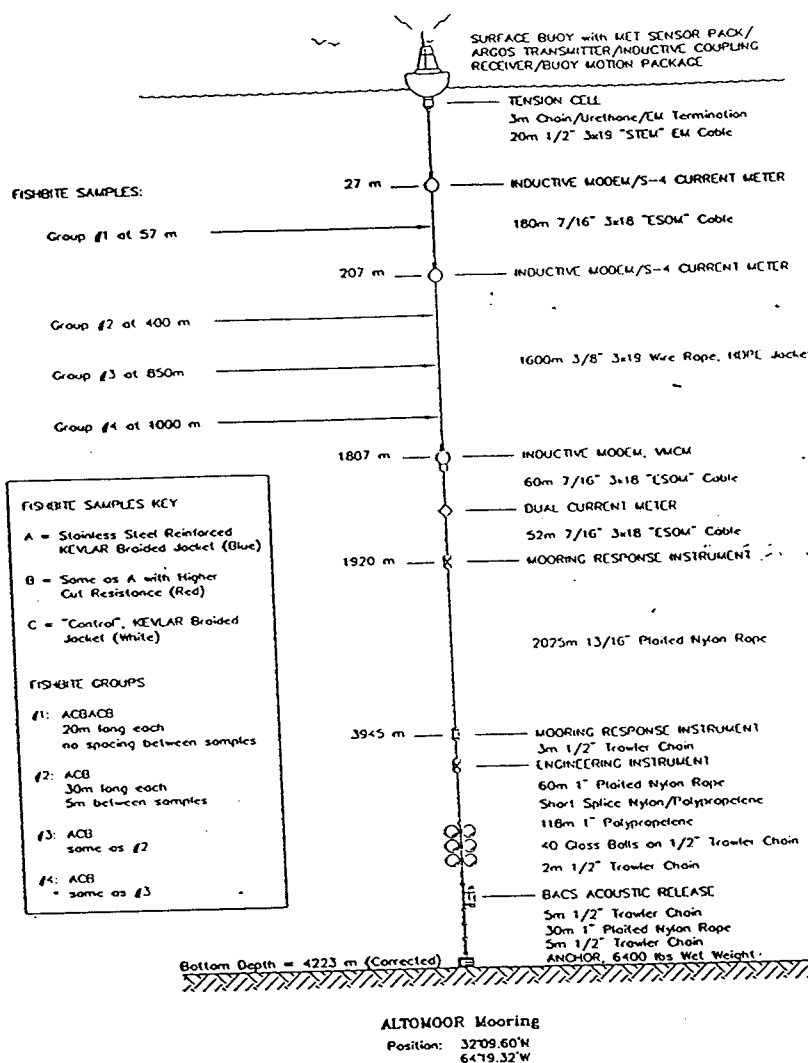


Figure 1: ALTOMOOR mooring configuration

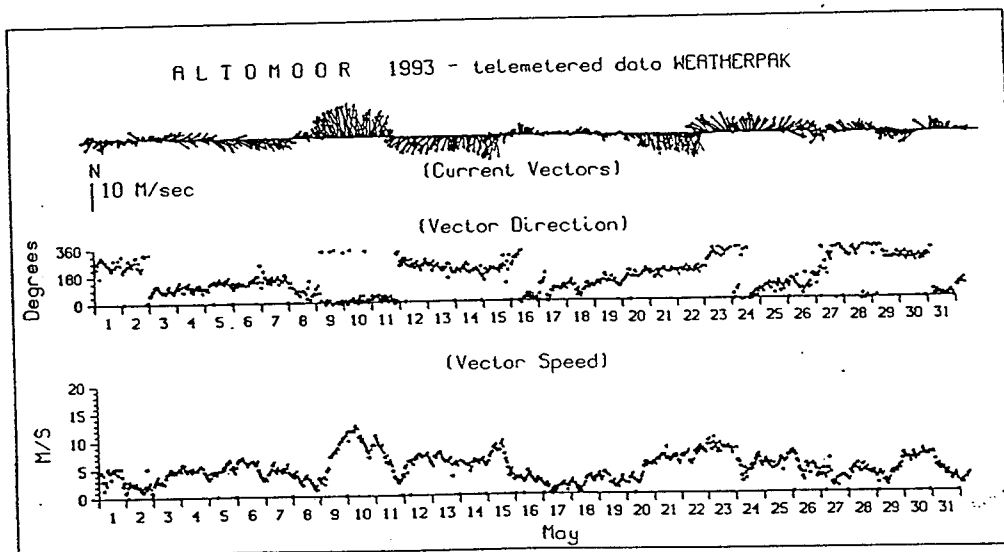


Figure 2: ALTOMOOR wind speed and direction, May 1993.

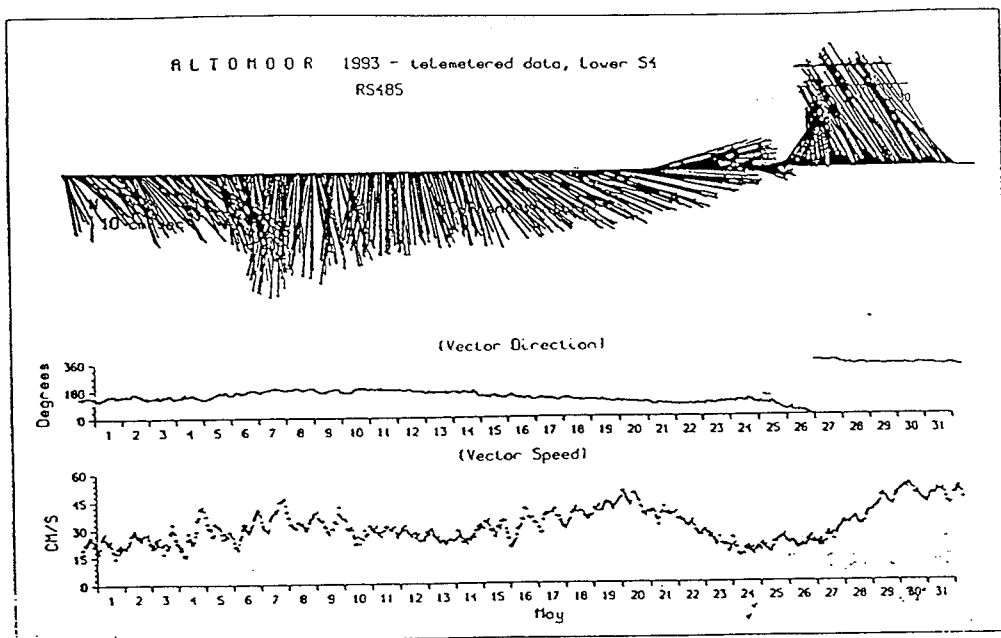


Figure 3: Currents from the S4 current meter at 200m for May 1993. Data telemetered via RS485.

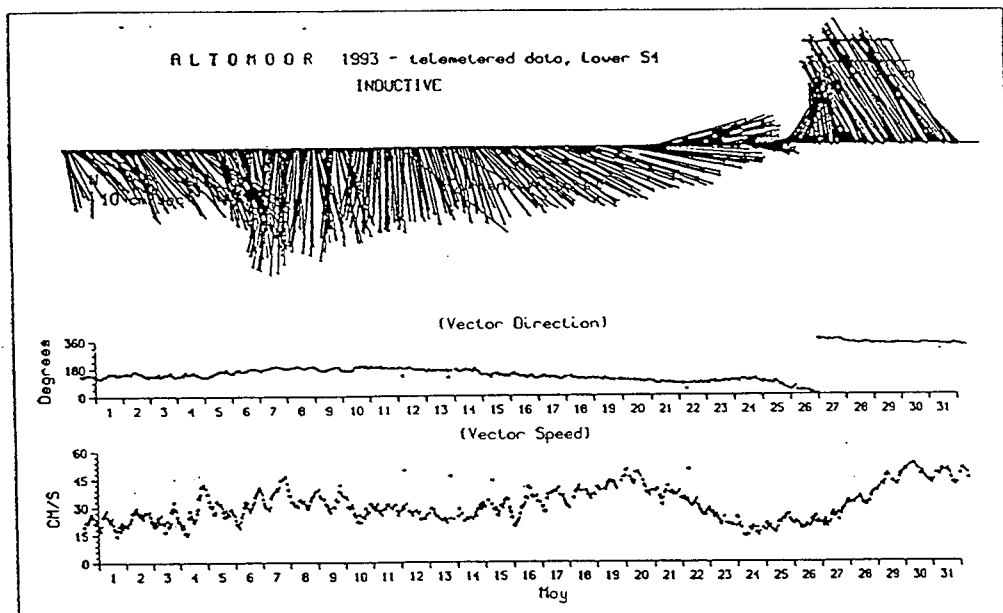


Figure 4: Currents from 200m S4 for May 1993. Data telemetered inductively.